Structural Analysis Results of Thermal, Operating and Seismic Analysis for Hanford Single-Shell Tank Integrity[1] - 12261

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ABSTRACT

Since Hanford's 149 Single-Shell Tanks (SSTs) are well beyond their design life, the U.S. Department of Energy has commissioned a state of the art engineering analysis to assess the structural integrity of the tanks to ensure that they are fit for service during the cleanup and closure phase. The structural integrity analysis has several challenging factors. There are four different tank sizes in various configurations that require analysis. Within each tank type there are different waste level and temperature histories, soil overburden depths, tank floor arrangements, riser sizes and locations, and other on-tank structures that need to be addressed. Furthermore, soil properties vary throughout the tank farms.

This paper describes the structural integrity analysis that was performed for the SSTs using finite element models that incorporate the detailed design features of each tank type. The analysis was performed with two different models: an ANSYS static model for the Thermal and Operating Loads Analysis, and an ANSYS dynamic model for the seismic analysis. The TOLA analyses simulate the waste level and thermal history and it included a matrix of analysis cases that bounded the material property uncertainties. The TOLA also predicts the occurrence of concrete thermal degradations and cracking, reinforcement yielding, and soil plasticity. The seismic analysis matrix included uncertainty in waste properties, waste height and the soil modulus. In seismic analysis the tank concrete was modeled as a linear elastic material that was adjusted for the present day degraded conditions. Also, the soil was treated as a linear elastic material while special modeling techniques were used to avoid soil arching and achieve proper soil pressure on the tank walls. Seismic time histories in both the horizontal and vertical directions were applied to the seismic model. Structural demands from both Thermal and Operating Loads Analysis and seismic models were extracted in the form of section forces and moments for sections throughout the tank under the appropriate load combinations. These demands were evaluated against the American Concrete Institute (ACI) code requirements for nuclear safety-related concrete structures as defined in ACI-349-06.

INTRODUCTION/BACKGROUND

Single shell tanks (SSTs) are underground nuclear waste storage tanks having a single liner of carbon steel housed within a cylindrical reinforced concrete structure. A total of 149 underground SSTs were constructed during the years 1943 through 1966. These SSTs are divided into 12 separate groups (based on their location) referred to as tank farms. The twelve tank farms are identified as A, AX, B, BX, BY, and C in the 200 East Area and S, SX, T, TX, TY,

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and U in the 200 West Area of the Hanford Site near Richland, Washington. There are 133 large capacity (530,000 758,000 and 1,000,000 gal) 100-Series tanks with a 75-foot internal diameter and 16 small capacity (55,000 gal) 200-Series tanks with a 20-foot internal diameter. Figure 1 shows a schematic of the 100 and 200-Series SST configurations. Tank geometry details, construction drawings and specifications are mentioned in greater detail in Han [1]. Julyk [2] summarized the construction date, steel liner material, and nominal wall thicknesses for each of the SST designs.

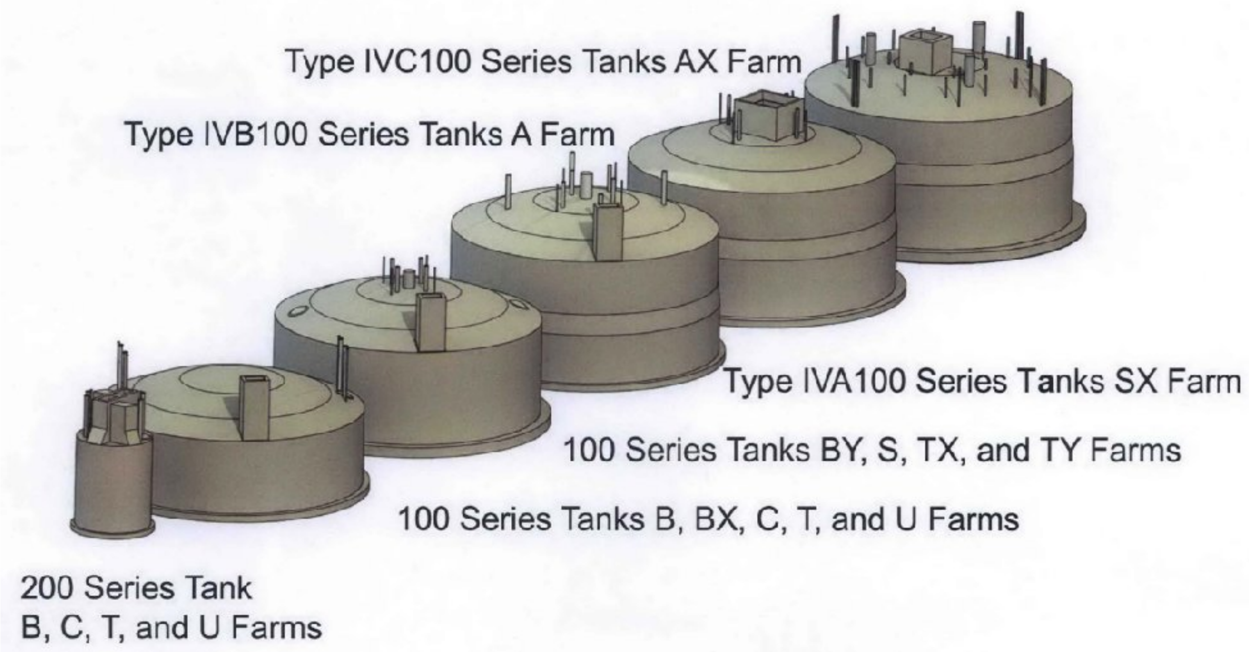

Figure 1. 100- and 200-Series Single-Shell Tank Configurations.

Continued safe use of these nuclear waste storage tanks is necessary until the tanks are cleaned and decommissioned by the US DOE sometime in the future. The safety of these aging structures during waste remediation campaign hinges on the understanding of the current condition (structural integrity) of these tanks. The structural integrity of the SSTs was analyzed using finite element models and this article provides a summary of the models and results for the Type II and Type III tanks.

ANALYSIS

The analysis was performed with two different models: a static model for the Thermal and Operating Loads Analysis (TOLA), and a dynamic model for the seismic analysis. A brief description of both models is provided below while the detailed description of these models is available in specific reports [12-13].

TOLA model

The TOLA of the Type II and Type III tanks was carried out using the commercial finite element (FE) software, ANSYS®. The geometric details for these tanks were taken from the construction

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® ANSYS Version 12.0 General Purpose Finite Element Program, ANSYS Inc., Canonsburg, Pennsylvania drawings. While both models were three-dimensional, two-degree slice models, a soil overburden of 10 ft for Type II tanks and 11 ft for Type III tanks was used to bound the respective tank types. Similar to the double shell tank (DST) TOLA analysis [3], the sub-grade undisturbed soil depth was specified at 168 ft below the foundation. To eliminate any influence of the soil boundary conditions on the tank, the radial extent of the soil (lateral soil dimension) was modeled to a radius of 240 ft, which is nearly seven times the radius of the tank. The ANSYS® SOLID185 (8 Node structural solid) elements were used to model the soil and SOLID65 (3-D Reinforced concrete solid) elements were used to represent concrete regions with and without reinforcement bars (rebar). The amount of reinforcement was specified as a volume fraction of the total element volume. Further details of the model are described in another paper presented at WM-2012 [4]. Figure 2 shows the finite element models of both the Type II and Type III tanks. The top portion of the figure shows the full extent of the Type II and Type III models with the concrete tank and soil layering. The bottom portion of the figure shows the zoom-in of the concrete tank and the adjacent soil. The grid size reflects the size of the finite elements.

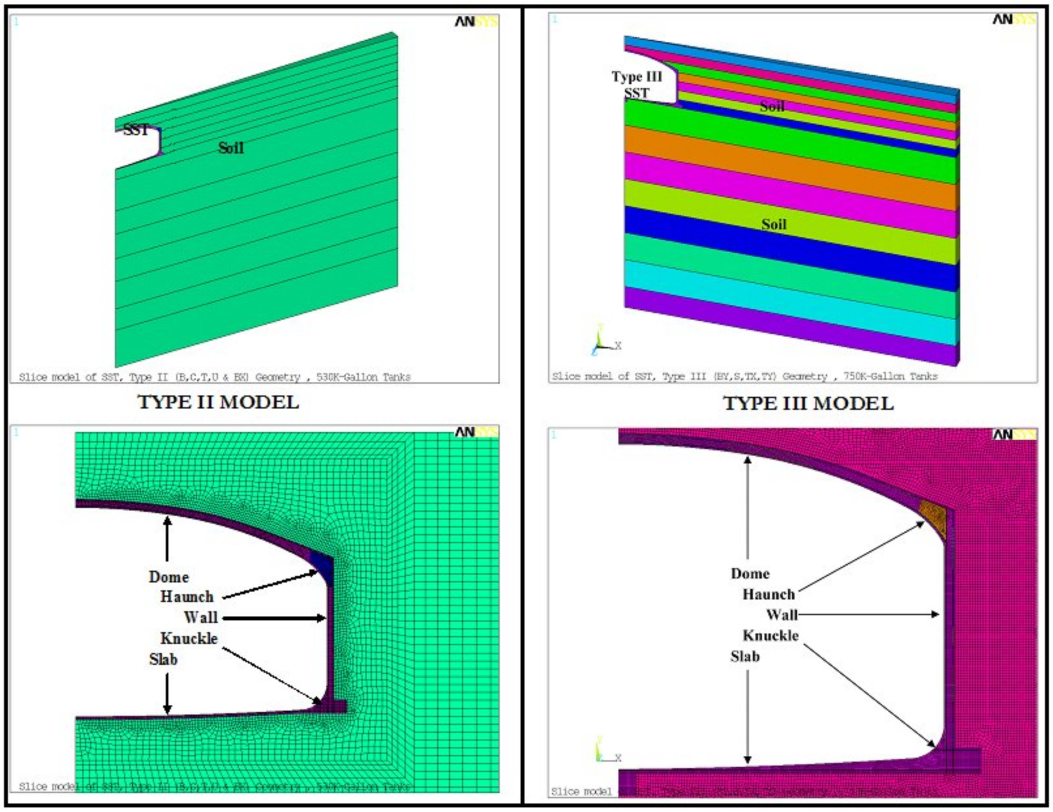

Figure 2. Finite element mesh of Type-II and Type-III SST TOLA models.

Material property data for concrete, soil, and reinforcing steel are not readily available due to the degrading effects of the buried reinforced concrete tank being exposed to high temperatures. A range of data (best estimate, lower bound, and upper bound) was provided in several reports [2-3] including the latest SST evaluation criteria report [5].

Best estimate, lower bound, and upper bound concrete strength and elastic modulus were provided as a function of temperature. Best estimate elastic modulus versus temperature was provided for the reinforcing steel. Best estimate, lower bound, and upper bound values were provided for the static stiffness properties of Hanford soils. A corresponding analysis matrix was developed for the TOLA model to account for the uncertainties in these material properties. Table I shows the final run matrix used for the Type III analysis. The Type II run matrix was similar to the Table I except for Run 7. A near zero value of 10 psi was used for concrete tensile strength based on the literature review of finite element models [6-9] and ACI evaluation criteria [10].

Table I. TOLA Run Matrix (Material Combination Strategy) for Type II & Type III SST AOR

Case/ Run	Soil	Concrete			Notes	
	Modulus	Modulus	Tensile Strength	Creep		
1	N	N	Near Zero (10 psi)	Yes	Best Estimate Properties	
2	N	N	Near Zero (10 psi)	No	“Worst-Case Combinations” Runs 2 – 8, use available material property bounds	Depending on depth, low soil modulus is lower by 20% to 50% when compared to best estimate values. Depending on temperature, high concrete modulus is higher by 15% to 30% when compared to best estimate values.
3	N	H	Near Zero (10 psi)	No		
4	L	H	Near Zero (10 psi)	No		
5	L	N	Near Zero (10 psi)	No		
6	N	N	(N) - Nominal	Yes		
7	L	N	Near Zero (10 psi)	Yes		
8	H	N	Near Zero (10 psi)	Yes		

H = High (Upper Bound).
L = Low (Lower Bound).
N = Nominal/Mean (Best Estimate).

Seismic model

The seismic analysis used a half-symmetry (180°) model of the SST, including the concrete tank and surrounding soil to evaluate the seismic loading including soil-structure interaction on the Type II and Type III SSTs. The concrete tank was modeled as a centerline (mid-thickness) shell model. The shell element properties used for the seismic model were determined for the predicted present-day condition of the concrete using TOLA Run 1. The soil was treated as a linear elastic material with modifications to soil regions over the tank to minimize the effects of soil arching. The correct at-rest side wall pressure was achieved by defining a small initial contact adjustment between the soil and the side wall of the tank. The complete model, including the SST and surrounding soil, is shown in Figure 3. The top portion of the figure shows the full extent of the Type II and Type III models along with the waste, concrete tank and the surrounding soil. The bottom portion of the figure shows the zoom-in of the concrete tank and the adjacent soil. The grid size reflects the size of the finite elements.

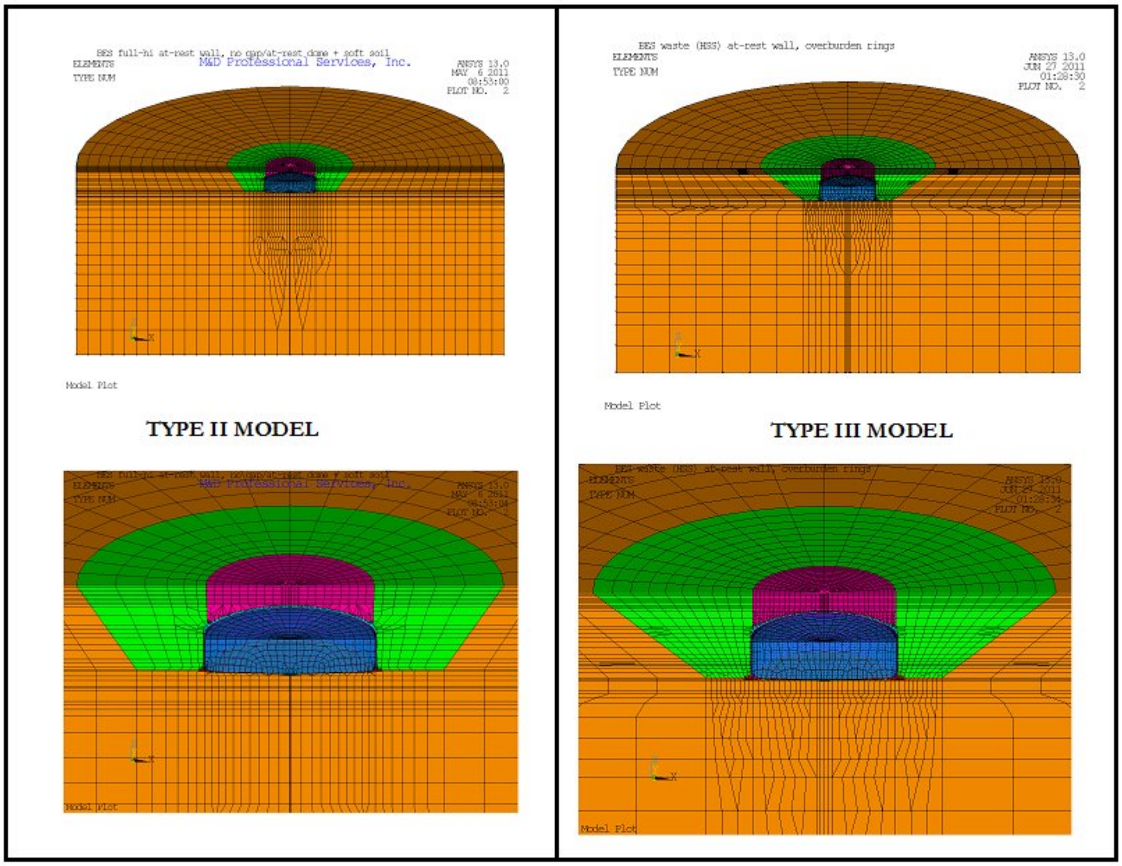

Figure 3. Finite element mesh of Type-II and Type-III SST seismic models [12, 13].

In addition to the material property uncertainties discussed in the TOLA models, seismic analysis is also dependent on waste height and waste properties. A corresponding analysis matrix was developed to account for the uncertainties in these material properties. Table II shows the final run matrix used for the Type II and Type III seismic analysis. Seismic time histories in both the horizontal and vertical directions were applied to the seismic model.

Table II. Seismic Model Run Matrix

Run	Soil	Backfill	Time History	Tank Concrete	Waste Height	Waste Properties
1	BES	BES	BES H + V	FCC	Empty	-
2	BES	BES	BES H + V	FCC	Full	LSS
3	BES	BES	BES H + V	FCC	Full	HSS
4	LBS	LBS	LBS H + V	FCC	Empty	-
5	LBS	LBS	LBS H + V	FCC	Full	LSS
6	LBS	LBS	LBS H + V	FCC	Full	HSS
7	UBS	UBS	UBS H + V	FCC	Empty	-
8	UBS	UBS	UBS H + V	FCC	Full	LSS
9	UBS	UBS	UBS H + V	FCC	Full	HSS

BES = Best Estimate Soil properties.
LBS = Lower Bound Soil properties.
UBS = Upper Bound Soil properties.
FCC = Fully Cracked concrete.
LSS = Low Shear Strength for waste properties.
HSS = High Shear Strength for waste properties.
H = Horizontal time history.
V = Vertical time history.

Loads

The loads for the evaluation of the SSTs were summarized in several reports, including Chapter 2 of Johnson et al. [5] and Appendix A of Rifaey [11]. The SST design loadings include those associated with normal operation, abnormal conditions, and extreme conditions. Table III lists the loading conditions used in this analysis. The 1.7 value of specific gravity chosen for the static TOLA analysis represents a conservative average waste density for the Type II and Type III tanks. The tank dead load, soil over burden, and hydrostatic waste loads were also applied with the appropriate boundary conditions. Additionally, a concentrated live load of 200,000 lb (representing a crane or other heavy equipment on the ground) was applied as a distributed load over a 10 ft radius on the ground directly above the center of the dome.

Table III. SST Analysis Load Conditions

	Design Load	Value	Notes
Type II Model	Design Life	25 to 35 years	A 65-year (1947–2011) design life is used
	Soil Cover	10 ft @ 125 lb/ft^3	Relative to dome apex
	Hydrostatic	variable height @ SpG =1.7	Specific gravity = 1.7
	Live Load	40 lb/ft^2	Uniform surface load
		200,000 lb	Concentrated over 10 ft radius
	Thermal	310°F	Maximum temperature of waste (tank center bottom)
	Seismic	H+V	See Table II
Type III Model	Design Life	25 to 35 years	A 59-year (1953–2012) design life is used
	Soil Cover	11 ft @ 125 lb/ft^3	Relative to dome apex
	Hydrostatic	variable height @ SpG =1.7	Specific gravity (SpG) = 1.7
	Live Load	40 lb/ft^2	Uniform surface load
		200,000 lb	Concentrated over 10 ft radius
	Thermal	300°F	Maximum temperature of waste (tank center bottom)
	Seismic	H+V	See Table II
	H + V = Horizontal and Vertical time history		

EVALUATION CRITERIA

SSTs were evaluated against the American Concrete Institute (ACI) code requirements for nuclear safety-related concrete structures as defined in ACI-349-06 [10]. The evaluation criteria report [5] provides a summary of the acceptance criteria using ACI-349-06 for application in the SST structural integrity evaluations, and it identifies the following specific load combinations that are applicable to the single-shell waste tanks.

Load Combination 1. $U = I.4D + 1.4F + 1.7L + 1.7H \quad (1)$
Load Combination 4. $U = D + F + L + H + T_o + E_{ss} \quad (2)$
Load Combination 9. $U = 1.05D + 1.05F + 1.3L + 1.3H + 1.05T_o \quad (3)$

where
U = Total load combination
D = Dead loads including tank self-weight, piping and equipment dead loads. (Where the structural effects of differential settlement, creep, or shrinkage may be significant, they shall be included with the dead load D.)
L = Live loads, including impact effects of moving loads
F = Lateral and vertical pressure of liquids
H = Loads due to weight and pressure of soil, water in soil, or other materials, or related internal moments and forces
T_o = Internal moments and forces caused by temperature distribution within the concrete during normal operation and shutdown
E_{ss} = Safe Shutdown Earthquake (SSE) effects = Design-Basis Event/Earthquake (DBE) effects

The factored load combinations shown in Equations (1), (2) and (3) are from ACI-349-06 [10] and account for the loading uncertainties. Figure 4 shows the flow chart used to model the SSTs with appropriate intervals for the ACI structural evaluation. Mechanical loads (gravity, waste load, and concentrated load) were applied in load steps 1 through 3. Thermal and waste level histories were applied in additional load steps with analysis ending at a waste temperature of 110°F. The analyses were then carried in two separate steps for respective ACI evaluations. In one step, the entire model was cooled down to 50°F after which the ACI load combination 1 load factors were applied for tank evaluation. In the other step, the waste was cooled to 80°F during which the ACI load combination 4 was evaluated followed by the evaluation of ACI load combination 9.

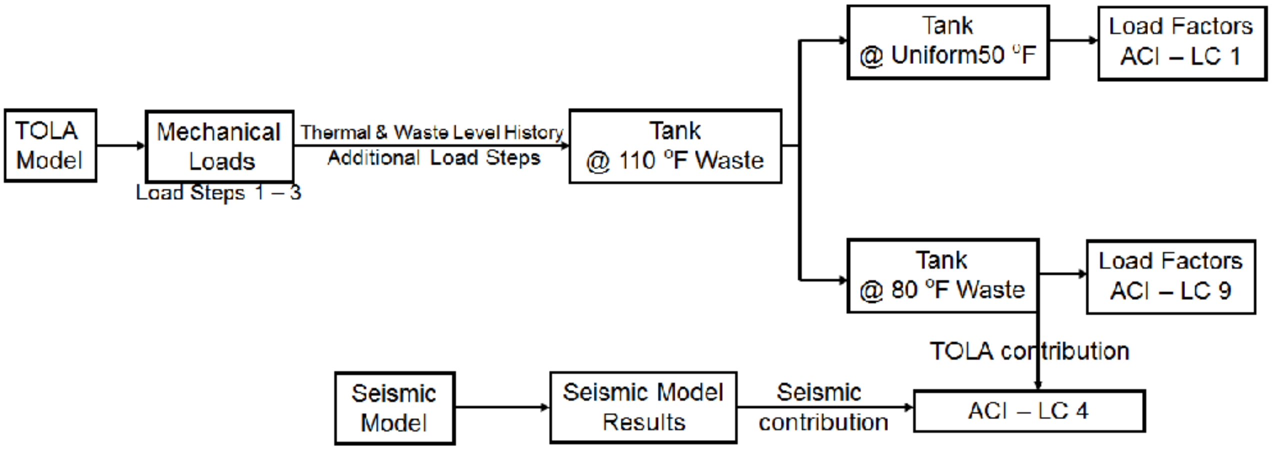

Figure 4. Flow Plan for SST AOR Analyses

Structural demands from both TOLA and seismic models were extracted in the form of section forces and moments for sections throughout the tank under the appropriate load combinations. Figure 5 shows the concrete tank (2-dimensional axi-symmetric front view without the surrounding soil) along with the section locations for both Type II and Type III tanks. Sections (Section 1) begin at the center of the dome and traverse through the haunch, down the wall and back across the slab. Capacities for these sections were evaluated using the ACI methodology defined in ACI-349-06 [10]. The ratio of demand to capacity was reported as a measure of structural integrity for the ACI load combinations shown in Equations 1, 2 and 3. A demand/capacity ratio exceeding 1.0 indicates that the ACI design requirements are not met.

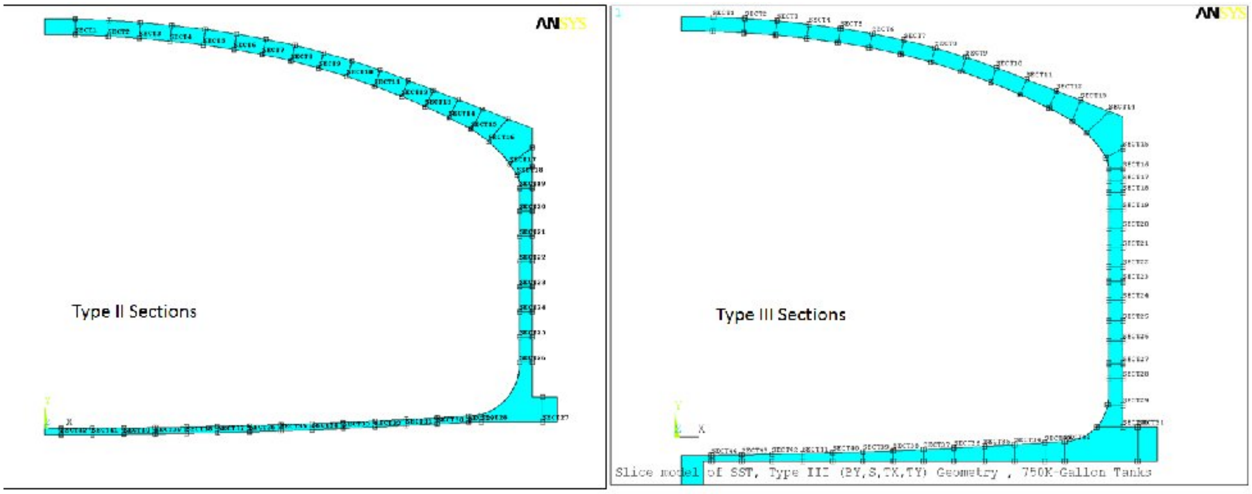

Figure 5. ACI section locations for Type II and Type III tanks. Section numbering starts near the dome apex (Section 1) and follows around the tank section to the center of the floor.

RESULTS AND DISCUSSION

Figures 6 through 8 shows the demand/capacity (D/C) ratios of Type II tank for run 1 (see Table I) of the TOLA run matrix using ACI load combinations 1, 4 and 9 identified in Equations (1), (2) and (3). The x-axes in Figures 6 through 8 show the section number and the y-axes shows the demand/capacity ratio of these sections in different directions. The demand/capacity ratios fluctuate as we traverse from the dome center to the slab center. The fluctuation is due to the change in section capacities from changing section properties (thickness, rebar volume and rebar orientation) and changing section demands from load redistribution due to concrete cracking and changing section properties. A demand/capacity ratio exceeding 1.0 indicates that the ACI design requirements are not met. Similarly, Figures 9 through 11 shows the demand/capacity (D/C) ratios of Type III tank for run 1 of the TOLA run matrix (see Table I) using ACI load combinations 1, 4 and 9 identified in Equations (1), (2) and (3).

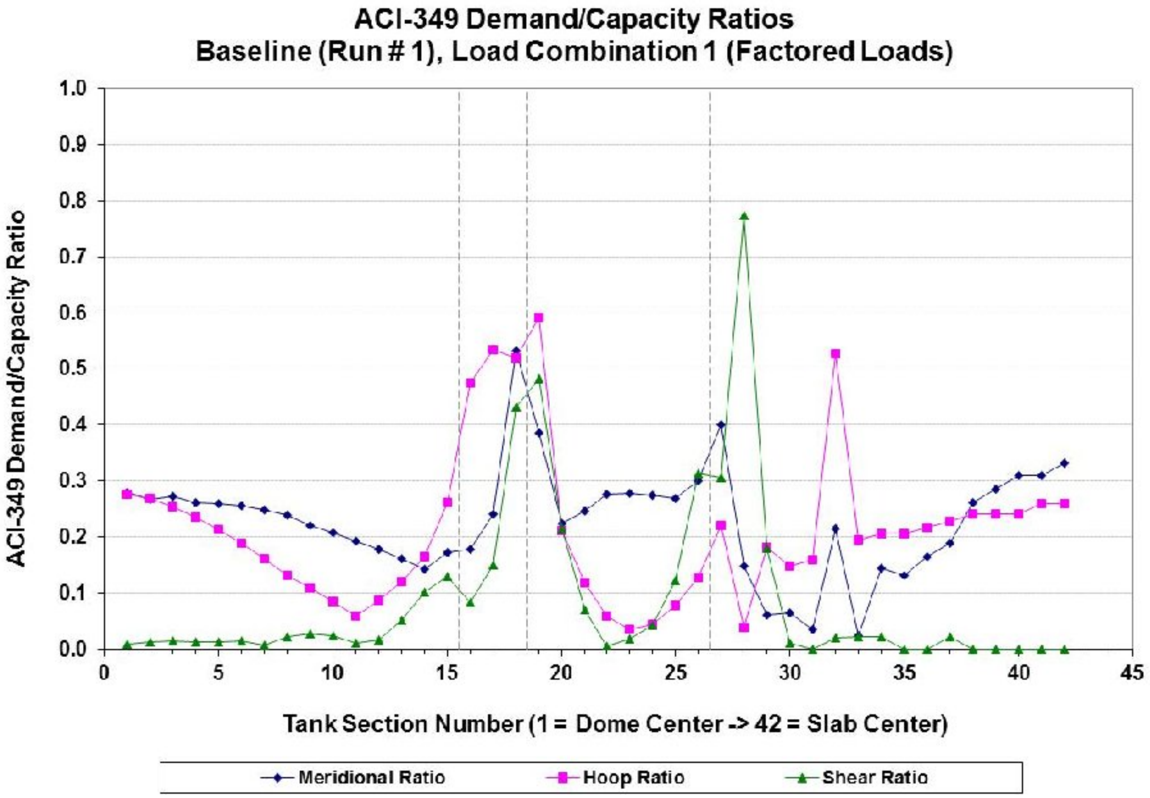

Figure 6. Type II tank TOLA Run 1, ACI D/C Ratios for LC1

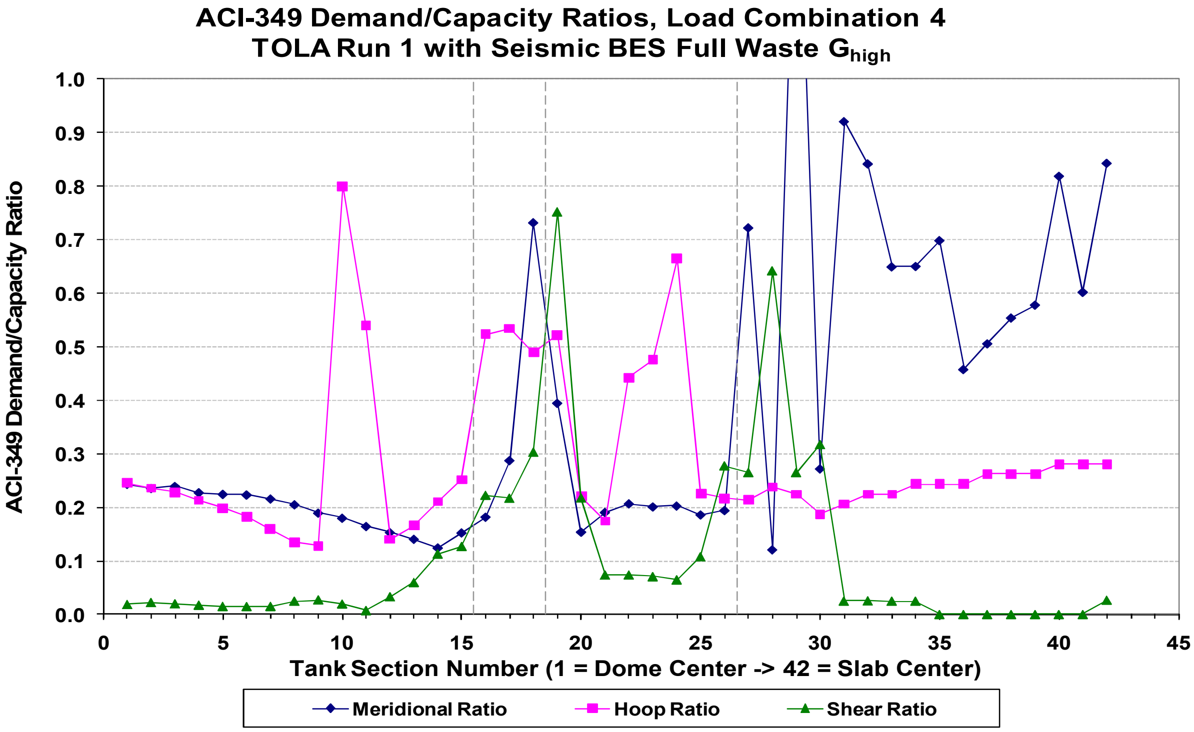

Figure 7. Type II tank TOLA Run 1, ACI D/C Ratios for LC4

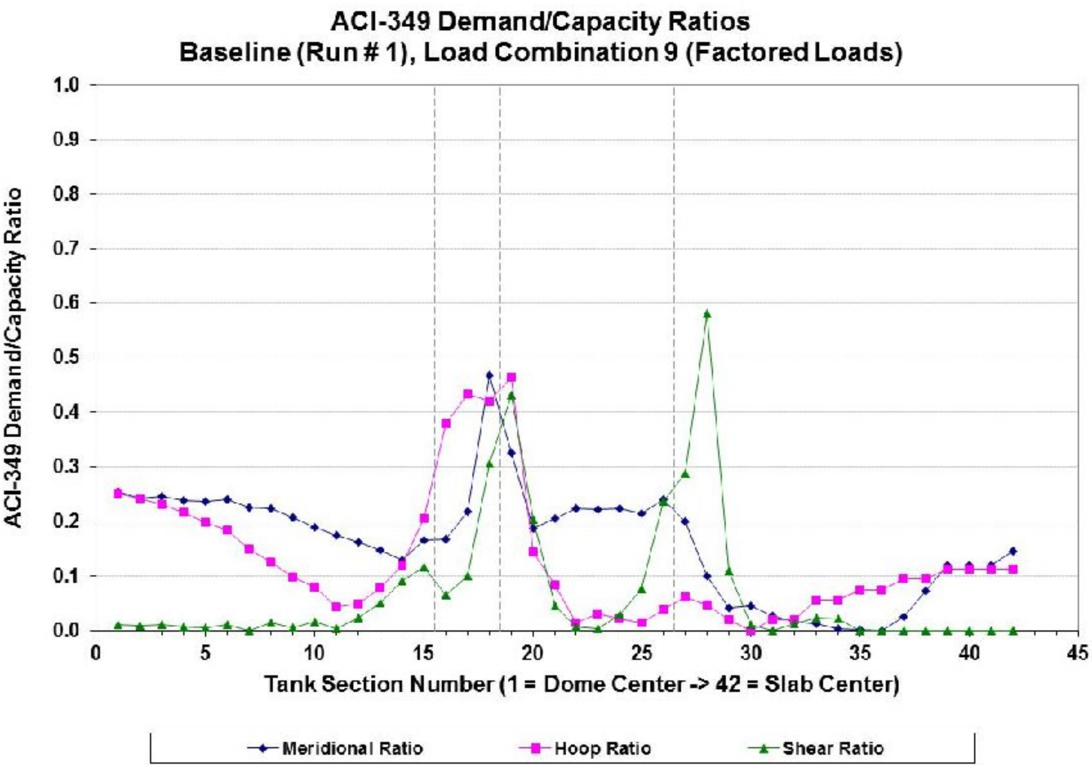

Figure 8. Type II tank TOLA Run 1, ACI D/C Ratios for LC9

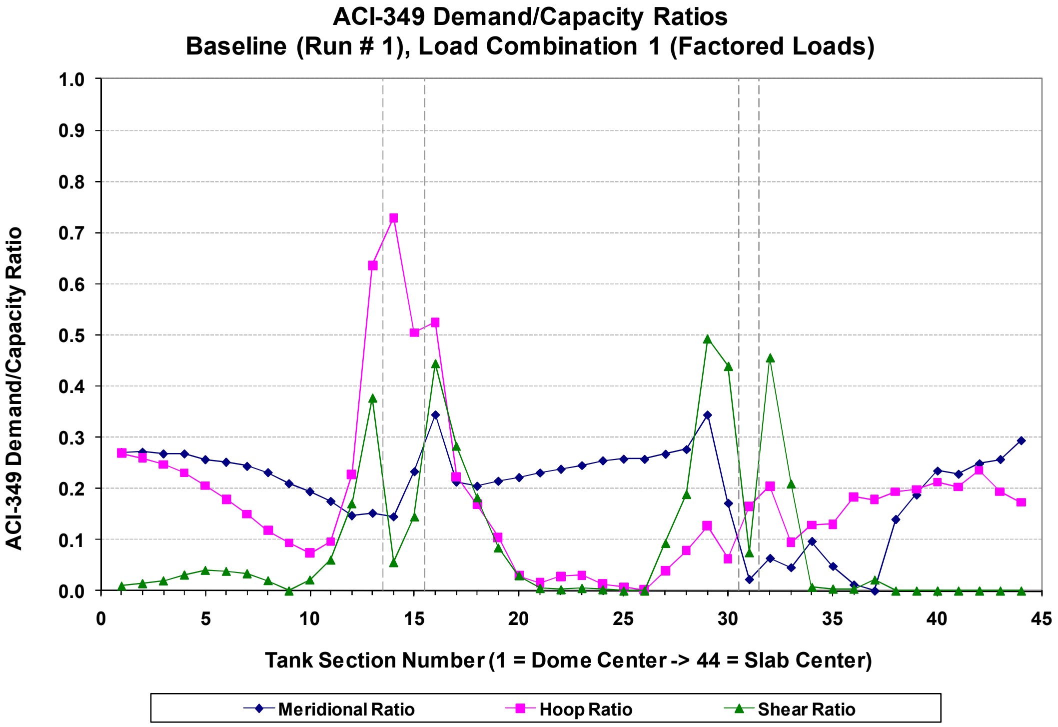

Figure 9. Type III tank TOLA Run 1, ACI D/C Ratios for LC1

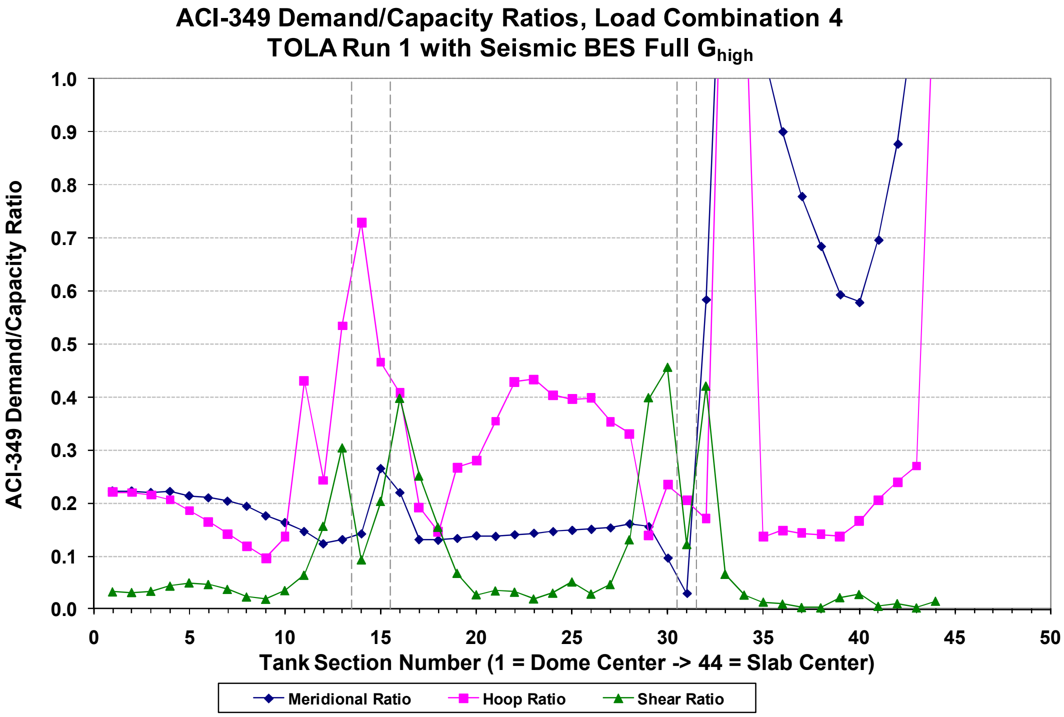
ACI-349 Demand/Capacity Ratios, Load Combination 4
TOLA Run 1 with Seismic BES Full G_{high}

Figure 10. Type III tank TOLA Run 1, ACI D/C Ratios for LC4

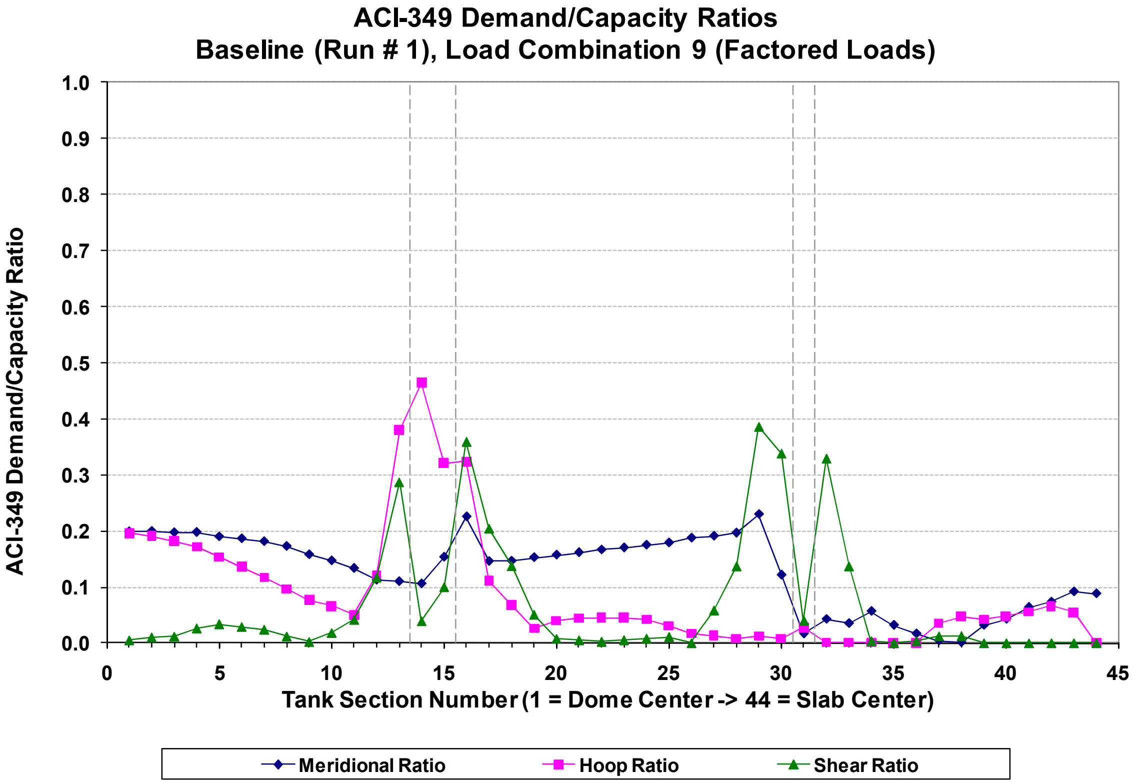
ACI-349 Demand/Capacity Ratios
Baseline (Run # 1), Load Combination 9 (Factored Loads)

Figure 11. Type III tank TOLA Run 1, ACI D/C Ratios for LC9

It is important to note in Figures 6 through 11 that the D/C ratios of the dome, haunch, and wall are less than 1.0 for all load combinations. However, Figures 7 and 10 show D/C ratios that are greater than 1.0 for a few slab sections. The slab has very little tension capacity compared with the rest of the tank. The ACI 349 slab tension capacity is calculated for one layer of ½-in.-diameter steel bars at 12-in. spacing. Even though the combined forces and moments within slab sections were small, these sections have very little capacity in tension. However, the slab is supported on soil and the cracking and displacements are displacement controlled. Cracks in the slab do not affect the structural stability of the tank dome walls and footing. Additional finite element analyses were performed with the slab separated from the tank footing to further evaluate the effect of possible cracking and shear offset of the concrete [12-13]. These additional analyses demonstrated that even in the event of local slab shear cracking, the slab-to-footing offset deformation was less than 40% of the steel liner thickness. The bottom and knuckle of the liner are also covered with a tar-based mastic material that would cushion the transition allowing the liner to bridge the small displacement offset without being damaged.

Results similar to those in Figures 6 through 11 were also generated for all the TOLA and seismic runs shown in Tables I and II. In all cases the D/C ratios of the dome, haunch, and wall were less than 1.0. These results were documented in detailed reports [12-13] but are not shown here for brevity. Therefore, all the tank regions (dome, haunch and wall) that are critical to the structural stability of the Type II and Type III tanks pass the ACI 349-06 acceptance criteria for the design of new structures. This is true for the conservative combination of maximum recorded thermal loads and maximum soil overburden depth combined with the run matrix of bounding material property combinations.

CONCLUSIONS

Structural integrity analysis of Hanford’s Type II and Type III Single-Shell Tanks (SSTs) was performed using finite element models (ANSYS software) that incorporate the detailed design features of each tank type. The analysis was performed with two different models: a static model for the Thermal and Operating Loads Analysis, and a dynamic model for the seismic analysis.

Structural demands from both Thermal and Operating Loads Analysis and seismic models were evaluated against the American Concrete Institute (ACI) code requirements for nuclear safety-related concrete structures as defined in ACI-349-06. The ratio of demand to capacity (D/C) was reported as a measure of structural integrity for the applicable ACI-349-06 load combinations. Although the Type II and Type III analysis matrix showed varying demands depending on the material combinations, all of the tank regions that are critical to structural stability passed the ACI 349-06 acceptance criteria. This was true for the conservative combination of maximum recorded thermal loads and maximum soil overburden depth combined with the analysis matrix of bounding material property combinations.

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